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Department of Biomedical Engineering

MRI-Compatible Cardiac Exercise Device

Mid-semester Report

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I. Abstract

The goal of this project is to develop an exercise device that can be used by patients in a magnetic resonance imaging (MRI) scanner in order to better understand and assess pulmonary hypertension. Currently, there is no device on the market that allows a patient to exercise while being scanned. After acquiring the dimensions of commercially available MRI bores, a model was constructed and various common exercises were tested within it. The exercises that worked well were then tested using standard, non-MRI-compatible equipment to determine their effectiveness at raising the heart rate to the target zone given by the client. Three preliminary designs were considered: leg extension, leg press, and stepper designs. After weighing the positive and negative aspects of these designs with respect to our design specifications and criteria, it was decided that the stepper design would be the best to pursue. The design will be made so that it can utilize either elastic or weight resistance. Some of the work that still must be done includes finalizing the device dimensions, ordering materials, and construction of the prototype. In addition, testing of the prototype for both effectiveness and MRI use is planned.

II. Problem Statement and Design Specifications

In order to better understand the effect of exercise on patients with pulmonary hypertension, Professor Naomi Chesler would like to use MRI to accurately measure changes in pulmonary blood pressure and flow during exercise. Our task is to develop an MRI-compatible exercise device for patients undergoing cardiac MRI scans. It should allow the patient to exercise while within the MRI bore and have adjustable workloads so patients of varying fitness levels can generate sufficient cardiac output.

There are several design requirements that the device must meet in order to be used effectively in a clinical setting. First and foremost, all materials should be MRI-compatible, meaning that no ferrous metals can be used. Non-ferrous metallic materials can be used if they are static and outside the scanner. In addition, the device must be reasonably sized to allow for easy transportation and storage, and have a weight that, when combined with patient weight, is less than the MRI scanner weight limit of 150 kg. The patient must be able to operate the device while lying within the bore. Of all major MRI models currently on the market, the smallest distance from the bed to the top of the bore is 42 cm [1]. Therefore, the device will be designed with these specifications so that it can be used with any scanner.

Another critical design specification is for the device to have an adjustable workload. Since the study will involve patients of a wide variety of fitness levels, the resistance level should be both measurable and variable for each patient. Moreover, the resistance should be sufficient to allow patients to reach the target heart rate zone, which is 70-80% of their maximum heart rate (220 beats/min – age). The exercise motion should be natural and fluid, with no risk for patient injury. Additionally, since the patient's torso will be scanned by the MRI machine, movement of the upper-body should be minimized. For additional details on product specifications, see **Appendix A.**

III. Background Information

Pulmonary Hypertension

Pulmonary hypertension is a disease characterized by increased blood pressure due to narrowing of the pulmonary arteries. This will lead to overworking and enlargement of the right side of heart (seen in **Figure 1**), as well as low blood oxygen concentration. Some potential causes of pulmonary hypertension are HIV infection, lung or heart valve disease, certain diet medications, and any condition that causes chronic low oxygen levels in the blood, among others [2]. Major symptoms of pulmonary hypertension include shortness of breath and light-headedness during activity, fast heart rate, swelling of the lower extremities, bluish color of the lips or skin, chest pain or pressure, dizziness, fainting, weakness, and fatigue [2]. To diagnose pulmonary hypertension, ECG, CT scans of the chest, and nuclear lung scans, as well as physical examinations, are performed [2].

Currently, there is no specific treatment for pulmonary hypertension. Rather, the major goal of treatment is focused on controlling the symptoms of the disease. Professor Chesler is interested in determining how exercise affects the blood pressure of pulmonary hypertension patients, in order to better understand the disease as well as assess the severity in each patient. A common way to execute this study is to have patients exercise outside of the MRI bore and then quickly perform the scan. However, this method is flawed because the time difference allows the patient's heart rate and blood pressure to recover from the effects of exercise. Her study will use MRI scanning to test the pulmonary blood pressure before, during, and after specific exercise. Therefore, she requires a MRI-compatible exercise device that can be used within the bore while a patient is being scanned.

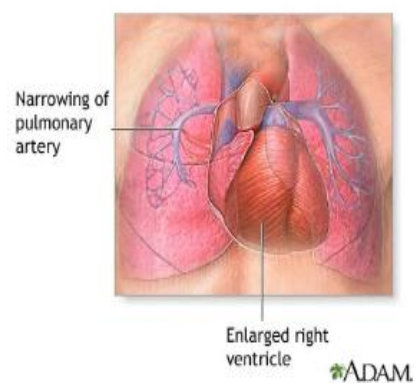

Figure 1 : The effects of pulmonary hypertension effects on the heart and pulmonary arteries [2]

Image courtesy of PubMed Health: *http://www.ncbi.nlm.nih.gov/pubmedhealth/PMH0001171/*

Competition and Past BME Designs

Several exercise devices have been designed for use with an MRI scanner. Lode B.V. provides several MRI-compatible devices that allow patients to exercise prior to MRI scans. These machines use a variety of exercise options, including cycling, ankle flexion, push/pull (seen in **Figure 2**), and up/down motions [3]. However, the major problem with these devices is that

Figure 2: The Push/Pull version of the Lode B.V. MRI Ergometer [3]

Image courtesy of Lode B.V. http://www.lode.nl/en/applications/mri_ergometry

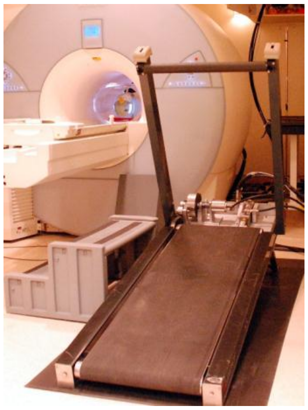

Figure 3: The MRI-compatible treadmill, designed by a team at Ohio State [6]

Image courtesy of MedCity: http://www.medcitynews.com/2009/05/commercialization-ramps-up-on-ohio-state-university-treadmill-used-for-mri-heart-tests/

they are much too expensive; the lowest price found was $28,000 [4]. In addition, most cannot be used during an MRI scan.

Another current product, the MRI-compatible treadmill, was designed by a team at Ohio State University. It is essentially a separate treadmill outside of the bore that has been completely modified to be compatible with the MRI environment [5]. This device can be seen in **Figure 3**. However, since exercise does not occur within the bore, this device has the problem of patient recovery between exercising and scanning, as mentioned above. Therefore, this device gives less accurate results than Professor Chesler desires.

Several UW-Madison Biomedical Engineering design teams have attempted similar projects in the past. One team spent two semesters (Fall 2009 and Spring 2010) working on a project with the same purpose and developed two prototypes. The first prototype was a cycling device, shown in **Figure 4**. The design team made a critical error by not designing the bike to fit the dimensions of the MRI bore. Therefore, when they attempted to test their prototype, the user's knees hit the edge of the bore which prevented them from completing the cycling motion. This resulted in the ultimate failure of their cycling design idea. Because of this, the team had to design a completely new prototype.

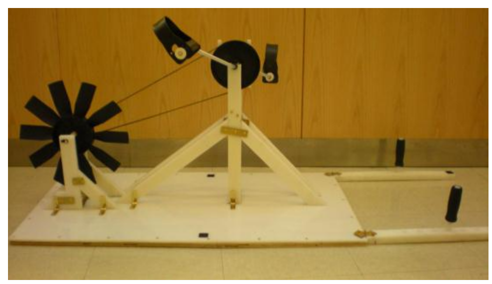

Figure 4: The cycling device developed by a UW-Madison biomedical engineering design team in Fall 2009 [7]

Image courtesy of UW-Madison BME Design: http://bmedesign.engr.wisc.edu/websites/project.php?id=29

Their second prototype was a stepping motion device that used two sliding foot pedals with fitness gear adjustable resistance tubes for the resistance (**Figure 5)**. The stepping motion of the device could be successfully completed while the user was in the MRI scanner; however, this prototype had several flaws. A major problem with the prototype was the large amount of friction generated between the foot pedals and the track. The design team did not mitigate this friction, leaving the two polyethylene surfaces to rub against each other during the motion. This decreased the smoothness of the stepping motion and reduced user comfort. Another problem with the prototype was the lack of support for the foot pedals. The foot pedals were held up by a thin brass facet and the resistance bands. This proved to be insufficient to withstand the force generated by the user. During testing and use following prototype completion, both pedals were broken. This shows that this prototype would have never withstood multiple patient trials. In addition to these structural

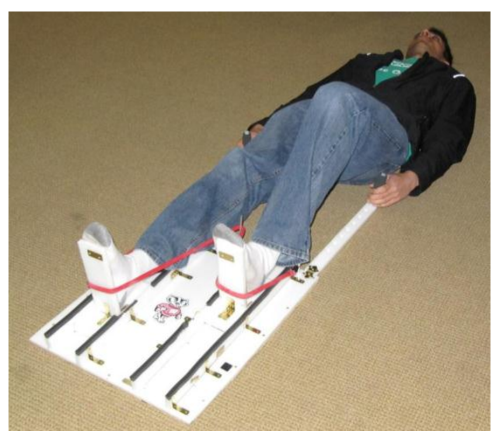

Figure 5: The stepper design, developed by the same group as the design in Figure 4 [8]

Image courtesy of UW-Madison BME Design: http://bmedesign.engr.wisc.edu/websites/project.php?id=295 defects, the prototype failed to generate sufficient resistance to allow the user to reach the target heart rate during exercise. According to the previous group's tests, the three subjects reached maximum heart rates of 88, 91, and 86 beats per minute, respectively [8]. That is only about 43-45% of their maximum heart rates, just barely more than half of the desired value. Due to these shortcomings, a more effective prototype is still needed.

In the fall of 2010, a separate BME design team developed another MRI compatible exercise device (**Figure 6**). This team designed their prototype for patients that would be subjected to MRI scans of the brain [9]. The nature of these brain scans allows for more of the patient's body to be out of the MRI bore. Therefore, it is likely that this prototype would not work for the reduced space restraints of a cardiac MRI scan without modification. In addition, this device has several other flaws. It is quite bulky, which makes transportation and storage exceedingly difficult and may intimidate patients. In addition, this device features an unnatural loading mechanism, where the resistance pulls up on the user's knees. This strange method of loading would most likely lead to increased patient discomfort. Given these reasons, a modification of this design will not be pursued.

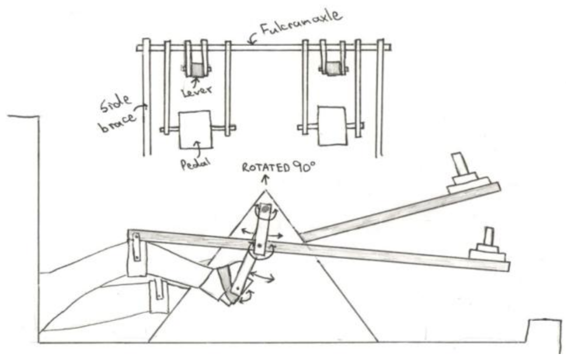

Figure 6: The device designed by a Fall 2010 UW-Madison biomedical engineering design team [9]

Image courtesy of UW-Madison BME Design:
http://bmedesign.engr.wisc.edu/websites/project.php?id=332

IV. Preliminary Testing

At the beginning of the design process, a model MRI bore was constructed. The dimensions of the bore were acquired in a SolidWorks file from Professor Darryl Thelen a faculty member at the UW-Madison Department of Biomedical Engineering. A variety of exercise motions were tested within this mockup in order to assess their viability. As a standard, the user placed the edge of the model bore at the middle of their thighs. Almost immediately the cycling motion was eliminated, as the user couldn't perform the motion without hitting their knees on the top of the bore. However, an assortment of motions that were possible within the bore were identified as potential options. In order to determine if these motions had the ability to raise the heart rate to the desired level, several exercise machines were experimented with at the SERF facility on the UW-Madison campus. The leg extension, leg-press, stair-climber (mimicking a stepper), and calf extension machines were all tested. The data collected from these tests is displayed in **Table 1**.

Table 1: Initial heart rate data collected at the SERF facility using exercise machines that were chosen to best simulate the motion of our potential prototypes – Nick Thate was the subject for all four tests

	Leg Extension	Leg Press	Stepper	Calf Machine
Time (min:sec)	3:30	3:00	3:00	1:20
Work Load	90 lb (41 kg)	170 lb (77 kg)	68 rpm	160 lb (73 kg)
Heart Rate (bpm)	158	134	164	123

Given these initial test results the leg extension, leg press, and stepper motions were identified as viable options. The calf exercise was eliminated because the desired heart rate range was not reached before the subject had to stop due to muscle discomfort and fatigue. The stepper was identified as the most comfortable motion with the least burning sensation in the muscles, and it was the most successful at raising the heart rate. The leg extension caused significant muscle fatigue, but according to the subject it felt like a more natural motion than the leg press. It must be stated that these results are not definitive, but they show trends that are helpful in identifying potential designs.

V. Design Options

Leg Extension Design

The leg extension design features a motion where the knees are stationary and the legs are repeatedly extended. In this design, shown in **Figure 7**, the patient's legs are laid over an adjustable support and straps placed over the ankles resist the extension motion. The resistance could come from bungee cords or resistance bands. The leg support is adjustable in the vertical and horizontal directions using a sliding pin mechanism, allowing for patients of various heights to fit comfortably into the device. One benefit of this device is the natural motion and the fluidity throughout the course of the movement. The patient would be able to extend their leg in whichever radius felt most comfortable to them. However, this same motion could cause problems because it isolates the quadriceps, which could result in muscle fatigue and discomfort.

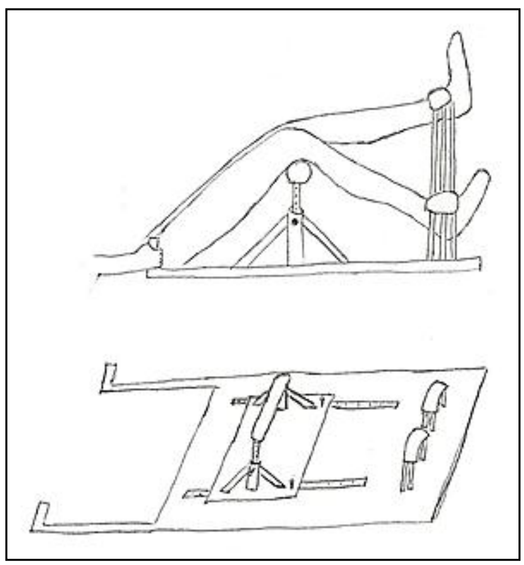

Figure 7: The leg extension design option

The relative small size and weight of this device would allow for easy transportation and storage, and ensure that the device is within the maximum load limit of 150 kg for the MRI couch. One concern for this design is the possibility of fatigue in the resistance bands between successive trials. This could cause a reduction in the resistance which could create complications when comparing different patient trials. Despite this the leg extension motion showed the ability to increase the patient's heart rate to the desired range in preliminary testing, and therefore shows promise to be a viable design.

Leg Press Design

The second design option is similar to an exercise machine called the leg press. In order to use this machine, the user pushes on the flat plate with both feet while lying in the supine position and holding the upper body still. When force is applied to the plate, it will rotate forward while the resistance causes the plate to push back against the patient's feet. This motion can be seen in **Figure 8**. After performing the preliminary exercise tests, it was determined that this design had the potential to effectively raise the heart rate to the target zone. Also, this design would be fairly easy to fabricate and would most likely be the most durable of the three. However, there are some drawbacks to this design. First, this type of exercise is meant for weight lifting not aerobic exercise, so performing the motion repeatedly is somewhat unnatural and causes muscle fatigue and burning. Second, this specific design would be the largest of the three designs, which is not ideal because there is a weight restraint and the client would like the device to be small. Finally, while performing the exercise, this device produces the most upper body movement, which is undesirable because the chest area is being scanned.

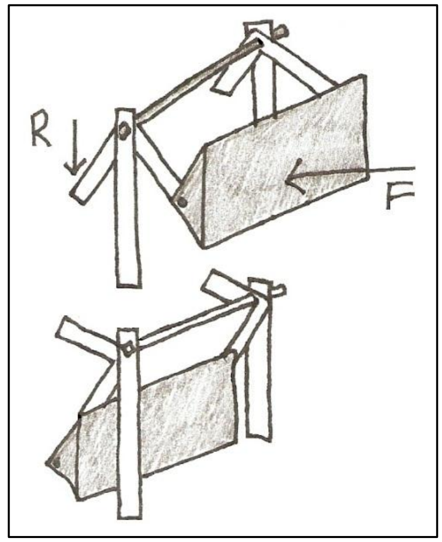

Figure 8: The leg press design option

Stepper Design

The third and final design is called the stepper, which was inspired by a stair-climber exercise machine. This design uses two levers, one for each foot, which the patient pushes against separately while in the supine position. When the patient pushes on the lever arm closest to them, it will rotate around a center axis, similar to the leg press, and there will be resistance pushing back against their feet. The stepper design can be seen in **Figure 9.**

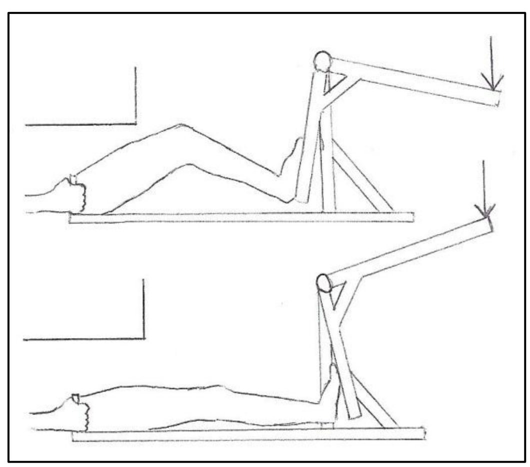

Figure 9: The stepper design option

This particular exercise device has many positive attributes. First, a similar exercise machine was able to raise the heart rate to the target zone when the preliminary exercise testing was performed, and the test subject described the motion as natural and comfortable with little to no muscle burning. Secondly, compared to the stepper design prototype fabricated by the past BME design team, this design will allow for a smoother motion with reduced friction. Although this design has many positives, there are also some negatives. The stepper device is composed of many moving parts that may require glass bearings, so there is more opportunity for pieces to break or wear out.

VI. Design Evaluation

In order to determine the best design to pursue for the remainder of the semester, the merits of the leg extension, leg press, and stepper design ideas were all weighed using a design matrix (**Table 2)**. Seven different criteria were deemed important for an effective design: patient comfort, motion mechanics, effectiveness, durability, ease of assembly, size/weight, and cost. Each of these criteria was then given a weight that corresponded to that criteria's relative importance. The three that were given the most weight were patient comfort, motion mechanics, and effectiveness.

Patient comfort is extremely important for this device because there is already some level of discomfort involved with being inside of the potentially claustrophobic MRI tube. The exercise device should not add to that by being uncomfortable or strenuous to use. Motion mechanics was defined as how natural and fluid the motion is for the patient. It should be feasible for even the most un-athletic of patients. Finally, the design must be able to raise the patient's heart rate to the target zone effectively. Therefore, effectiveness was considered one of the most important criteria.

Each of the designs was rated on a 0-10 scale for each of the seven criteria. These scores were then multiplied by their weight and totaled, giving an overall design score on the same 0-10 scale. The design matrix, complete with each design's scores, can be seen below in **Table 2**.

Table 2: The design matrix used to weigh the pros and cons of each design option, which ultimately resulted in the stepper design being chosen

Weight	Criteria	Leg Extension	Leg Press	Stepper
0.2	Patient Comfort	6	7	9
0.2	Motion Mechanics	9	7	8
0.2	Effectiveness	8	7	9
0.15	Durability	6	8	7
0.1	Ease of Assembly	8	7	6
0.1	Size/Weight	9	6	8
0.05	Cost	9	7	7
	Weighted Average	**7.65**	**7.05**	**8**

As seen in the design matrix above, the stepper design scored the highest, with a score of 8/10. It was followed by the leg extension (7.65/10) and the leg press (7.05/10). It managed high scores in the three most highly weighted categories, which helped lead to it being chosen as the best design. As a result, the stepper design will be pursued.

VII. Final Design and Future Work

One of the major considerations for the final design was the type of resistance to motion that would be used. The two methods considered were resistance via elastic force (using bands or bungee cords) and weight resistance. Elastic resistance would be light-weight and very portable, while weights are heavy and bulky. This is a concern because there is a physical restriction on the amount of weight the MRI table can hold and Professor Chesler would like the device to be portable and easily stored. Consistency of resistance is also very important. The bands can give differing amounts of resistance as they stretch as well as fatigue over time; weights have none of these problems, and provide consistent and easily measurable resistances.

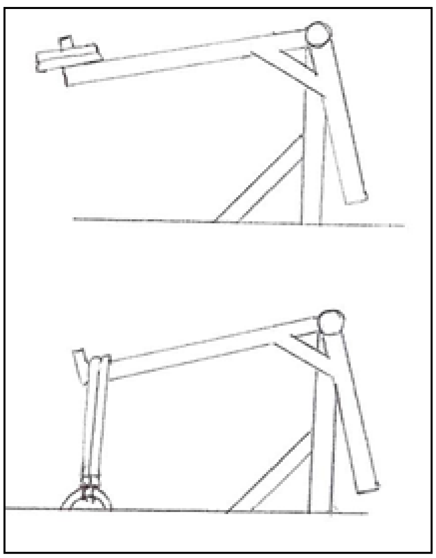

Figure 10: The stepper design can be designed to be used with either elastic or weighted resistance

After some deliberation and brainstorming, it was determined that the device could be designed in a way that it could use *either* elastic or weighted resistance. The design in **Figure 10** shows that the only difference in the requirements for each type of resistance would be a small hook at the base of the design for elastic resistance. By making the device compatible with both weights and elastic bands, the two resistances can be tested and compared with one another to determine which is more effective. It also offers additional flexibility to potential users.

Now that the design is chosen, materials for its components need to be selected. Ideal materials would be strong, non-ferrous, and inexpensive. After consulting with Professor Thelen, who has experience designing MRI-compatible exercise devices to study individual muscle groups, it was determined that the bulk of the device should be fabricated out of high-density polyethylene (HDPE) and Delrin. Delrin is a stronger polymer, but it is also more expensive. Therefore, it will likely be used only for the components that are determined to require substantial mechanical strength. The components will be secured together using brass fasteners, and rotation elements will incorporate glass bearings. Before any materials are assembled and tested, they will be tested to ensure MRI-compatibility.

There is still much work to be done to make the prototype as effective as possible. The ideal dimensions of the device need to be determined. The team will take futher measurements in the MRI facility to ensure that the device is designed to fit on/around the MRI table and can be positioned correctly for use during scans. As soon as materials arrive, fabrication will begin. Finally, the prototype will be constructed and assembled on a component-by-component basis.

Once the device is made, it will undergo several stages of testing. First, the team will test its overall effectiveness at increasing heart rate to the target zone. Then it will be taken to the MRI facility where it will be tested within the scanner. Finally, MRI scans will be performed on the team members before, during, and after exercise with the device, to help aid in pulmonary hypertension research and diagnosis. If these initial scans are successful, the device will have to apply for IRB approval to use the device in human studies.

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IX. Appendix A: Product Design Specifications

Problem Statement

In order to better understand the effect of exercise on patients with pulmonary hypertension, Professor Naomi Chesler would like to use MRI to accurately measure changes in pulmonary blood pressure and flow during exercise. Our task is to develop an MRI-compatible exercise device for patients undergoing cardiac MRI scans. It should allow the patient to exercise while within the MRI bore and have adjustable workloads so patients of varying fitness levels can generate sufficient cardiac output.

Client Requirements

- MRI-compatible
- Comfortable supine exercise motion
- Sufficient resistance to increase cardiac output
- Adjustable workload

Design Requirements

1. Physical and Operational Characteristics
    a. *Performance requirements:* The device should provide a natural exercise motion that can be performed while the patient is within the MRI bore. The workload provided must increase the patient's heart rate to >70-80% of their maximal predicted heart rate, which is equal to 220 beats/min minus the patient's age. It needs to be adjustable for various patient fitness levels and sizes (150-200 cm).
    b. *Safety:* All materials must be MRI-compatible (non-magnetic) for the safety of the patient, scanner, and medical staff. The exercise motion cannot put the patient at risk for injury during use.
    c. *Accuracy and reliability:* The design should provide consistent workload settings from patient-to-patient. All patients should be able to reach the target pulmonary blood pressure.
    d. *Life in service:* The device must be able to withstand clinical use for five years.
    e. *Shelf life:* N/A
    f. *Operating environment*: The design will be used in clinical or research settings in the presence of an MRI scanner and ECG leads.
    g. *Ergonomics:* The motion should be natural, fluid, and controlled without any undesirable friction.

h. *Size:* The device must allow for exercise within the bore of any MRI scanner. The standard measurements of the bore are 42 cm from the couch to the top and 60 cm in width.
i. *Weight:* The weight on the couch cannot be greater than 150 kg, so the device will not exceed 25 kg. Individual components should not weigh more than 15 kg to ensure portability.
j. *Materials:* All components must be durable and made of non-ferrous materials.
k. Aesthetics, appearance, and finish: The device should be quiet and not intimidating to the user.

2. Product Characteristics
   a. *Quantity:* One working prototype
   b. *Target product cost:* $150.00

3. Miscellaneous
   a. *Standards and specifications:* Must pass inspection for use in MRI and eventually be IRB approved for human trials
   b. *Customer:* Hospitals, clinics, and research labs
   c. *Patient-related concerns:* Comfortable, safe, and durable
   d. *Competition:* Lode B.V. MRI Ergometer, prototypes from other universities, and past and present UW BME design projects